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ADDITIONAL DESIGN STUDIES OF THE NASA/NAVY LIFT/CRUISE FAN

by

GENERAL ELECTRIC COMPANY

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16. Abstract

Additional preliminary design studies were performed for a turbotip lift/cruise fan propulsion system for a Navy multimission aircraft. The LCF459/J97 propulsion system was previously designed for this application. These studies extended the analysis in areas of (1) scroll commonality, (2) increased engine-out contingency ratings, (3) mounting systems, (4) manufacturing cost reductions and (5) vulnerability.

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SUMMARY

The design studies of the LCF459 advanced remote turbotip lift fan are reported in Reference 1. This report presents the results of additional studies performed related to this propulsion system in the particular areas of:

Scroll commonality as required to meet typical installations incorporating either two or three fan systems.

Performance to provide increased contingency ratings during the emergency engine-out condition.

Mounting systems for close coupled fan and engine systems.

Fan manufacturing cost reductions

Scroll vulnerability to projectile impact and lubrication failures

Reference to the original design studies is recommended to establish the background required before leading into these studies.

SCROLL COMMONALITY

The geometry of a turbotip fan scroll is established by the number of fans and gas generators used in the system and the location of the propulsion components in the aircraft. Two particular engine/fan combinations are of prime interest for the Navy multimission aircraft. These are three fans with two gas generators and two fans with two gas generators. In the two on two system, a third gas generator is installed in the aircraft to provide pitch control in addition to transfer of flow to the fans in the event of engine failure. These two configurations establish scroll arc operating requirements as given in Table I. This summary shows the many operating arc options that are required for a scroll configuration which would be common to both systems.

With this design goal defined, the task was undertaken to define a scroll configuration for the LCF459 which could be used for either installation with none or only minor modifications. The scroll configuration, as shown in Figure 1, was defined as a solution. The scroll contains a single entry with capability of operating with a full 360 degrees of admission arc. The scroll is fabricated in three sections which are joined together with bolted flanges. A blocker or divider plate is installed at the flange joint opposite the inlet to provide two 180 degree arc segments. The scroll section adjacent to the inlet duct attachment contains both an inner and outer shell. The inner shell provides the flowpath for feeding two adjacent 60 degrees of arc. The area formed by the annulus between the inner and outer shell provides the flowpath to feed the outer segments or arcs of the scroll. Closure valves or doors located at the inlet to the scroll may be used to close off the flow to the inner shell, thus giving an operating scroll arc of 240 degrees. The many arc-of-admission options available for this scroll configuration are shown in Figure 2.

An additional benefit achieved by this method of scroll construction is obtained through the use of the double wall configuration. Here, the

scroll pressure vessel skins are scrubbed by hot gas during 240, 300 and 360 degree arc operation. For previous scrolls, during 240 degree operation, part of the scroll pressure vessel would run cooler than the rest of the structure and thus generate thermal stresses which required added structural weight. This new design will experience more uniform structure temperatures and thus lower thermal stresses which permit the utilization of less exotic material, Hastelloy X versus René 41. The more uniform structure temperature also provides a better flowpath alignment between the turbine stators and blades than for the case where one part of the scroll is unheated.

The estimated weight of this new scroll configuration is the same as the 111 kg (245 lb) weight of the original single bubble scroll. Additionally, for the same weight, a reduction of fan projected frontal area is achieved. The original scroll configuration, sized for a three fan/two gas generator installation, had a frontal area of 3.768 sq m (5840 sq in) as compared to this redefined scroll with the same installation capability, which has an area of 3.387 sq m (5250 sq in).

PERFORMANCE STUDIES

The design guidelines for the Navy multimission aircraft specify the need for vertical landing capability following failure of any one of the gas generators. The aircraft gross weight at this condition shall include 453.6 kg (1000 lbs) of fuel with no internal or external stores.

The original LCF459 performance studies showed that a three fan/two engine system was capable of producing a 97.78 kN (21,981 lb) thrust level with only one gas generator operating at the emergency power rating with four percent combustor water injection. During the initial aircraft studies, this level of emergency thrust exceeded the emergency landing weight of the aircraft. As the studies were continued and refined, the empty weight of the aircraft increased until the emergency thrust requirement became 111.20 kN (25,000 lbs), which exceeded the capabilities of a two engine system. A study was then performed to determine engine cycle changes which would be required to provide this required thrust rating, while still retaining the basic design of the LCF459 fan system.

Prior to describing the particular studies performed, a short discussion of general levels of contingency thrusts is desirable. A typical aircraft may employ variable numbers of gas generators, either with or without interconnect. Assuming the typical aircraft gross weight and thrust requirements as shown in Table II, contingency thrust requirements, as a function of numbers of engines were determined. Figures 3 and 4 show the engine thrust ratios required to meet the general aircraft criteria. The need for engine interconnect, either by hot gas or mechanical means, is apparent as indicated by a large reduction in contingency thrust requirements. For a two engine aircraft, as presently being considered, the contingency thrust ratio with interconnect becomes about 1.28. For a three engine aircraft, the need for high contingency thrusts vanishes and is no longer a propulsion system design requirement.

For these studies of the LCF459/J97 system the thrusts as given in Table II were used as an objective. Two basic approaches were used to achieve these objectives:

Oversize the engine compressor, flow and pressure ratio, so that significant thrust improvements can be achieved without excessive temperature increases as the engine speed is increased.

Rematch the power extraction of the gas generator and fan turbines so that the contingency thrusts can be achieved without overspeeding the engine into the regions of low compressor efficiency.

Pre-combustor water injection was considered for both cases as a method of engine temperature reduction. Compressor inlet water injection is a possible alternative to combustor water, but was not considered in these studies because of the difficulty in predicting the effects on compressor performance. Compressor water injection is expected to be the more efficient method in terms of amount of water required, but will require considerable development testing.

The design approach used in the study considering an oversized compressor was as follows:

The compressor design point at the design mechanical speed was assumed to remain fixed for all designs and at the values established for the original Growth J97 engine. The compressor pressure ratio was 16.7 at an inlet airflow of 36.30 kg/sec (80.03 lb/sec) at 100 percent compressor speed.

The compressor aerodynamic design point was established at some engine overspeed condition, such that as the compressor speed is increased, the performance continues at some high level of efficiency. Basically, this yields compressors with increased flow capacity and pressure ratio over that required during normal engine operation.

Three compressor designs, as described in Table III, were considered in this study. Figure 5 shows the compressor operating characteristics for these three designs at the overspeed operating conditions. The improvements at high engine speeds can be observed as the compressor oversize is increased. One each of these engine cycles was used to drive three LCF459 fans, equivalent to the engine-out case. Performance was determined with four and six percent combustor water and is summarized in Figure 6. The engine-out thrusts are established by operating the engine to the speed/temperature limits as shown in Figure 7.

These characteristics indicate that a compressor with a design pressure ratio of 21, including six percent combustor water, would be required to give an engine-out thrust of 111.20 kN (25,000 lbs). The estimated maximum pressure capability for a single spool compressor is 19, and at this condition the engine-out thrust would fall about 454 kg (1000 lbs) below the objective.

The second method investigated to provide increased engine out thrust levels involved a redistribution of the energy extraction of the gas generator and fan tip turbines. The energy extraction of each turbine can be adjusted by changing the area of the turbine inlet stators or nozzles. The procedures used in this study to rematch the turbines was as follows:

The original Growth J97 engine compressor was used.

The engine turbine area was increased, which would lower the compressor operating point to a lower pressure ratio.

The fan turbine area was decreased until the compressor operating point moves up to the design level.

With the engine areas retrimmed as above, the turbine inlet temperature exceeds limits. Combustor water injection is used to reduce the engine turbine temperature.

The engine operating speed for these conditions must then be

readjusted to meet the speed/temperature limits as previously defined by Figure 7.

This procedure was used to determine engine-out performance for a range of turbine area variations, with either four or six percent combustor water. The results are summarized in Figure 8, and show that the 111.20 kN (25,000 lb) level can be obtained by increasing the engine turbine area by 10 percent, while using six percent combustor water injection. The fan turbine area is reduced approximately 15 percent.

During engine-out operation of a three fan/two engine configuration, each fan is driven by one third of the operating gas generator flow. The 15 percent reduction of turbine area during the engine-out condition can be established by selectively sizing the turbine arc receiving the engine flow. The split of areas of the fan turbine is summarized in Table IV.

For engine-out, the scroll arc would be 29.9 percent, or 108 degrees, as required to retrim the engine. For normal VTO operation, the scroll area as required for the original engine cycle will be retained. This will cause a mismatch of the engine with the compressor operating at a lower operating condition, with some increase in temperature. During cruise, each fan would be interconnected to a single engine, with a fan turbine area equal to the sum of engine-out and normal VTO areas.

A comparison of the two methods for increasing the engine-out contingency rating shows that the turbine rematch method is by far the most easily achieved. The performance of the LCF459/J97 system was updated to reflect this revised cycle matching and is reported in Reference 2. The reference gives both cruise and V/STOL performance. Engine and fan performance at sea level static conditions are listed in Table V, and are compared to performance data for the original cycle. These data were generated for an installed propulsion system using the same installation factors as previously used and listed in Tables VI and VII.

PROPULSION MOUNTING

During the initial design studies of the LCF459/J97 lift fan system, several mounting systems were considered. The mounting systems fall into one of two categories:

Separate, remote mounting of the gas generators and fans

Integral or close-coupled mounting of the fan and engine as a single unit

One requirement for the separate mounting method is that the pressure/area or piston forces due to bellows attachments may not be transmitted into the engine or fan structure. This necessitates the use of tied or pressure compensated bellows, which may be difficult to install within the desired installation envelope. By close coupling the engine and fan, this requirement no longer exists.

A study was conducted to determine the most desirable method of mounting a close coupled fan and engine system. The recommended mounting scheme is shown in Figure 9. This arrangement employs a non-redundant mounting of both the engine and fan. The only axis of restraint common between the two units is an axial tie between the engine exhaust and scroll inlet through a double ball joint in the transition duct. The ball joints restrain the separating force of the ducting but permit lateral and rotational motion between the two flanges. This arrangement differs from the original integral mounting system given in Reference 1, in that a double ball joint is used in place of a single joint. The double ball joint permits the use of two vertical and side mounts on the engine. These double mounts reduce the engine case bending moments to a level more comparable to the case of a conventional turbojet engine.

FAN MANUFACTURING COSTS

The Navy currently evaluates engine production costs, for planning and budgetary purposes, using a material parameter derived by R. J. Maurer, commonly called the "Maurer" factor. This costing method is described in detail in Reference 3. It has been established as having a significant statistical correlation of engine production cost and the product of material input weight and an exotic material factor, thus the "Maurer" factor is:

$$MF = \sum_{1}^{N} w_n W_n \qquad n = \text{Number of Materials}$$

where "W" is the weight of material used in the manufacture of the engine component and "w" is the material index factor. The material index factor is divided into six categories as given in Table VIII. The material index factor is a weighting factor including both the relative material and manufacturing or conversion costs. All titanium is classified in one category while the conventional materials such as stainless steel, carbon steels and aluminum are classified as conventional and assigned the unit base level. A breakdown of the most common materials by material index factor is given in Table IX.

A study was performed to determine the potential cost reductions, based on this method of evaluation, which could be achieved through material substitutions. Wherever possible, material changes were made in the LCF459 components to materials of lower classification. Table X compares the original and revised low-cost materials for each component. Changes of material were made only in those areas where these changes would represent no compromise in design criteria and negligible changes of weight. The changes of the scroll material from Rene 41 to Hastelloy X was permitted because of the new scroll design which experiences lower thermal gradients and thus lower stresses. The frame change to a material of lower temperature capability will require a minor design change to include film cooling of the struts where they pass through the hot turbine flowpath.

One problem in using the "Maurer" factor for this evaluation is that the weight of material is based on input weight, not finished part weight. The recommended scrap factor used by the Navy in cost evaluation of the LCF459 was 0.75. This means that four times as much material is required than the weight of the fi ished part. For a fan weight of 401 kg (885 lbs), the total material would be 1606 kg (3540 lbs). This scrap factor is greater than General Electric experience in the manufacture of a wide range of aircraft gas turbine components and engines. For consistency in evaluation, the 75 percent scrap factor will be used in the following comparison.

Table XI gives the Maurer factor calculation for the original LCF459 fan design and indicates an index of 61,112. For the fan design ing low "Maurer" factor material, the index becomes 36,263 as shown in Table XII. Based on this costing method, this comparison indicates that a cost reduction of about 40 percent could be obtained through minor design changes of the LCF459 which would permit these material changes.

A cost evaluation was also conducted for the two fan designs using General Electric methods which are based on cost experience for manufacture of similar engine components. This analysis showed an estimated cost reduction of 20 percent between the two same fan designs.

Both of these cost evaluations indicate that a reduced cost fan design can be obtained through careful consideration of the types of materials used for the components. When advanced technology materials are used or required, they should be used to their maximum capability.

VULNERABILITY

The vulnerability/survivability of the LCF459 was evaluated in two areas:

- Capability of withstanding multiple strikes of 14.5 mm API projectiles
- Capability of the bearings to operate without oil following a lubrication failure

The vulnerability to projectile strikes was evaluated using the theory of fracture mechanics of the scroll material. This analysis method relates fracture toughness of the material, local stress levels and critical crack length. Critical crack length is the maximum crack size which can be tolerated without very rapid crack propagation. The threat assumed in the analysis was the 14.5 mm API projectile which has a maximum diameter of 1.49 cm (0.586 in) and a maximum length of 5.13 cm (2.022 in). Penetration of the scroll pressure vessel skin was assumed to occur for a "tumbled" projectile. The crack length produced by the puncture was estimated to be 5.33 cm (2.10 inches), slightly larger than the projectile length.

The analysis of the capability of the original LCF459 scroll showed that the critical crack length was only 1.88 cm (0.74 inches) in certain high stress areas of the scroll skin. Through local skin thickening, at an added scroll weight of 2.5 kg (5.5 lbs), the crack length capability becomes as shown in Figure 10. Crack lengths of 5.33 cm (2.10 inches) spaced at intervals of 7.87 cm (3.1 inches) could be sustained by the scroll and still permit completion of the mission without a catastrophic or explosion-like scroll failure.

The redesigned compatability scroll, as previously described in this report, was also analyzed to establish the crack length capability. This scroll maintained similar capabilities, as shown in Figure 11, but without any added weight over the original scroll weight of 111 kg (245 lbs).

The improved capability was achieved through the lower operating stress of the uniformly heated scroll skins.

Another desirable capability of the turbotip fan was established through analysis of the bearing system to operate without oil, typical of a lubrication system failure. Using experience based on actual operation of the CF6 and TF39 engines without bearing lubrication, the capability of the LCF459 was established. Two particular cases were studied, operating capability at full VTO power levels and operating capability at low power settings required for low speed cruise. The analysis showed that the system could operate for 13 minutes at VTO power levels. At low power settings, the operating time becomes 42 minutes, which provides a range of about 241 km (150 miles). Sufficient operating time remains after the 42 minutes to permit a vertical landing, which was estimated to require the equivalent of one minute operation at VTO power.

CONCLUSIONS

The additional studies of the LCF459 turbotip fan, as described in this report, have yielded the following results:

An attractive multi-shell scroll configuration has been defined which minimizes the thermal stresses associated with partial arc operation and provides a wide variety of scroll operating arcs as required for commonality with the numerous aircraft installations.

Significant fan cost reductions are possible through selective changes of materials. Estimated cost reductions of 20 to 40 percent are anticipated, based on the method of cost evaluation. Some minor fan design changes are required with no significant change of fan total weight.

Studies of engine changes required to increase the engine-out thrust levels have shown that turbine area matching can increase the engine-out thrust from the original level of 9,970 kg (21,981 lbs) to 11,360 kg (25,046 lbs). This change requires an increase of 10 percent in the engine turbine nozzle area and selective matching of the fan turbine nozzle area.

Vulnerability studies have shown that the LCF459 can sustain multiple strikes by a 14.5 mm API projectile without experiencing explosive type scroll failures.

Sustained operation is estimated to be adequate for return and landing of the aircraft following a fan lubrication failure.

REFERENCES

1. General Electric Company, Aircraft Engine Group, Cincinnati, Ohio: NASA/Navy Lift/Cruise Fan Preliminary Design Report, NASA Contractor Report CR-134837, July, 1975.

2. General Electric Company, Aircraft Engine Group, Cincinnati, Ohio: LCF459/J97 Estimated Performance with Rematched Turbine Areas, Report Number R75AEG479, November, 1975.

3. Brennan, T. J. and Taylor, R. N.: Cost Estimating Techniques for Advanced Technology Engines, Society of Automotive Engineers Technical Paper Number 700271, April, 1970.

TABLE I - SCROLL ADMISSION ARC REQUIREMENTS

Operating Mode	Two Fans on Two Engines (degrees)	Three Fans on Two Engines (degrees)
Normal Cruise	360	360
Engine-Out Cruise	180	240/120
Normal VTOL	360	240
Engine-Out VTOL	300	120

TABLE II - TYPICAL AIRCRAFT WEIGHTS AND REQUIRED THRUSTS

STO Weight	18, 140 kg (40, 000 lbs)
VTO Weight	13, 830 kg (30, 500 lbs)
V-Landing Weight	11, 340 kg (25, 000 lbs)
Take-Off Thrust, STO and VTO	142. 3 kN (32,000 lbs)
Landing Thrust, Engine-Out	111.2 kN (25,000 lbs)

TABLE III - COMPRESSOR DESIGN POINT PARAMETERS

Design Speed (Percent)	Pressure Ratio	Flow (lb/sec)	Flow (kg/sec)
106.3	20.7	91.9	41.7
104.2	18.9	86.6	39.3
102.0	17.3	82.0	37.2
ORIGINAL GROWTH J97 COMPRESSOR			
100.0	16.7	80.0	36.3

TABLE IV - FAN TURBINE AREA REMATCH

	Original			Modified		
	(sq in)	(sq cm)	(pct)	(sq in)	(sq cm)	(pct)
Engine-Out	47.2	305	33.3	40.2	259	29.9
Normal VTO	94.4	609	66.7	94.4	609	70.1
Cruise	141.6	914	100.0	134.6	868	100.0

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TABLE V - PERFORMANCE WITH REMATCHED TURBINE AREAS

(Installed, Sea Level Static, Hot Day)

	Original Cycle			Modified Cycle		
	Cruise (2 on 2)	VTO (3 on 2)	Engine-Out (3 on 1)	Cruise (2 on 2)	VTO (3 on 2)	Engine-Out (3 on 1)
Ambient Temperature, °K (°R)	288.15 (518.67)	305.37 (549.67)	305.37 (549.67)	288.15 (518.67)	305.37 (549.67)	305.37 (549.67)
Gas Generator Speed, percent	100.9	101.9	110.0	97.6	100.6	101.5
Inlet Airflow, kg/sec (lb/sec)	35.92 (79.21)	34.33 (75.68)	35.32 (77.87)	34.66 (76.42)	33.73 (74.37)	34.21 (75.24)
Compressor Pressure Ratio	16.77	16.35	18.10	14.91	14.72	16.44
Turbine Inlet Temperature, °K (°R)	1464 (2635)	1467 (2640)	15[illegible]4 (27[illegible])	1449 (2[illegible])	14[illegible] (2640)	1592 (2865)
Turbine Discharge Temperature, °K (°R)	1029 (1852)	1061 (1909)	1140 (2052)	1078 (1940)	1081 (1945)	1236 (2224)
Turbine Discharge Pressure, kN/m^2 (lb/in^2)	377.0 (54.67)	366.1 (53.10)	408.0 (59.18)	390.4 (56.62)	363.4 (52.71)	493.6 (71.59)
Turbine Discharge Flow, kg/sec (lb/sec)	36.27 (79.97)	34.85 (76.83)	37.38 (82.42)	35.04 (77.26)	34.26 (75.54)	36.94 (81.43)
Engine Fuel Flow, kg/hr (lb/hr)	2531 (5581)	2489 (5487)	3373 (7437)	2624 (5784)	2520 (5555)	3915 (8631)
Combustor Water Flow, kg/sec (lb/sec)	0 (0)	0 (0)	1.306 (2.88)	0 (0)	0 (0)	1.891 (4.17)
Fan Speed, percent	99.28	90.30	75.44	101.2	90.20	86.67
Fan Airflow, kg/sec (lb/sec)	286.9 (632.6)	259.9 (572.9)	218.4 (481.6)	292.5 (644.9)	259.6 (572.3)	234.1 (516.0)
Fan Pressure Ratio	1.314	1.215	1.143	1.324	1.215	1.165
Total Thrust, kN (lb)	139.1 (31260)	144.7 (32530)	97.8 (21981)	142.5 (32026)	144.2 (32417)	111.4 (25046)

TABLE VI

INSTALLATION ASSUMPTIONS FOR VTOL OPERATION

Engine Inlet Recovery	0.985
Ducting Pressure Loss, percent	3.10 Lift Fan 9.47 Nose Fan
Engine Compressor Bleed, percent	0.5
Engine Power Extraction, kW (hp)	18.6 (25)
Fan Inlet Recovery	0.985
Exhaust Nozzle Thrust Coefficient	0.940
Fan Shaft Power Extraction, kW (hp)	37.2 (50)
Ducting Total Pressure Loss, percent	3.1
Fan Stall Margin, percent *	27

* Fan Nominal Operating Line Gives Stall Margin = 18%, VTO Operation at 25% Gives Maximum Static Thrust.

TABLE VII

INSTALLATION ASSUMPTIONS FOR CRUISE PERFORMANCE

Engine Power Extraction, kW (hp)	18.6 (25)
Fan Shaft Power Extraction, kW (hp)	18.6 (25)
Engine Compressor Bleed, percent	1.0
Ducting Pressure Loss, percent	3.1
Nozzle Thrust Coefficient	0.98
Fan Stall Margin, percent	20

Mach Number	Engine Inlet Recovery	Fan Inlet Recovery
0.0	0.985	0.985
0.2	0.989	0.993
0.4	0.990	0.995
0.6	0.990	0.994
0.8	0.987	0.980
0.9	0.984	0.970

TABLE VIII. MATERIAL WEIGHTING FACTORS

Classification	Weighting Factor
Titanium	10.50
Conventional	1.00
"A"	6.65
"B"	13.95
"C"	24.50
"D"	29.50

TABLE IX - MATERIAL CLASSIFICATIONS

"A"	"B"
Low Alloy Steels	N-155
Stainless Steels	Stellite 6
Greek Ascoloy	Hastelloy B
AM350	Hastelloy C
AM355	Hastelloy X
17-4 PH	702
17-7 PH	722
19-9 DL	X-750
PH 15-7 Mo	901
W-545	Inconel 706
A-286	
600	
801	

"C"	"D"
713	U-500
Inconel 100	Waspaloy
L605	Rene 41
M-252	Astroloy
Inconel 718	
Inconel 625 (Sheet)	
Hastelloy W	
Stellite 30	
Stellite 31	

TABLE X - FAN MATERIAL SELECTION CHANGES

Component	Original	Reduced-Cost
Turbine Blades	R-80	Inconel 100
Frame	Inconel 718	17-4 PH
Sump Housing	Titanium 6-4	Titanium 6-4 (36%) Aluminum 7075
Casing	Inconel 718	Inconel 706
Turbine Seals	Hastelloy X	321 Stainless Steel
Scroll	Rene 41 (92%) Hastelloy X (7%) Inconel 625 (1%)	Rene 41 (16%) Hastelloy X (80%) 321 Stainless Steel (4%)

All Other Components have the Same Material as in Original Design

TABLE XI

"MAURER" FACTOR EVALUATION OF ORIGINAL LCF459 FAN DESIGN

- Material Scrap Factor - 0.75

	Output Weight		Input Weight (W)		Material	Maurer Factor	
	lb	kg	lb	kg	Index (w)	lb	kg
	96	44	384	174	1.0	384	174
	280	127	1120	508	10.5	11760	5334
	36	16	144	65	6.7	965	438
	59	27	236	107	14.0	3304	1499
	200	91	800	363	24.0	19200	8709
	214	97	856	388	29.8	25509	11571
Totals	885	402	3540	1606		61122	27724

TABLE XII

"MAURER" FACTOR EVALUATION OF REVISED LCF459 FAN DESIGN

- Material Scrap Factor = 0.75

	Output Weight		Input Weight (W)		Material	Maurer Factor	
	lb	kg	lb	kg	Index (w)	lb	kg
	120.9	54.8	484	219	1.0	121	55
	274.0	124.3	1096	497	10.5	11508	5220
	157.0	71.2	628	285	6.7	4208	1909
	244.6	110.9	978	444	14.0	13692	6211
	36.0	16.3	144	65	24.0	3456	1568
	27.5	12.5	110	50	29.8	3278	1487
Totals	860.0	390.0	3440	1560		36263	16448

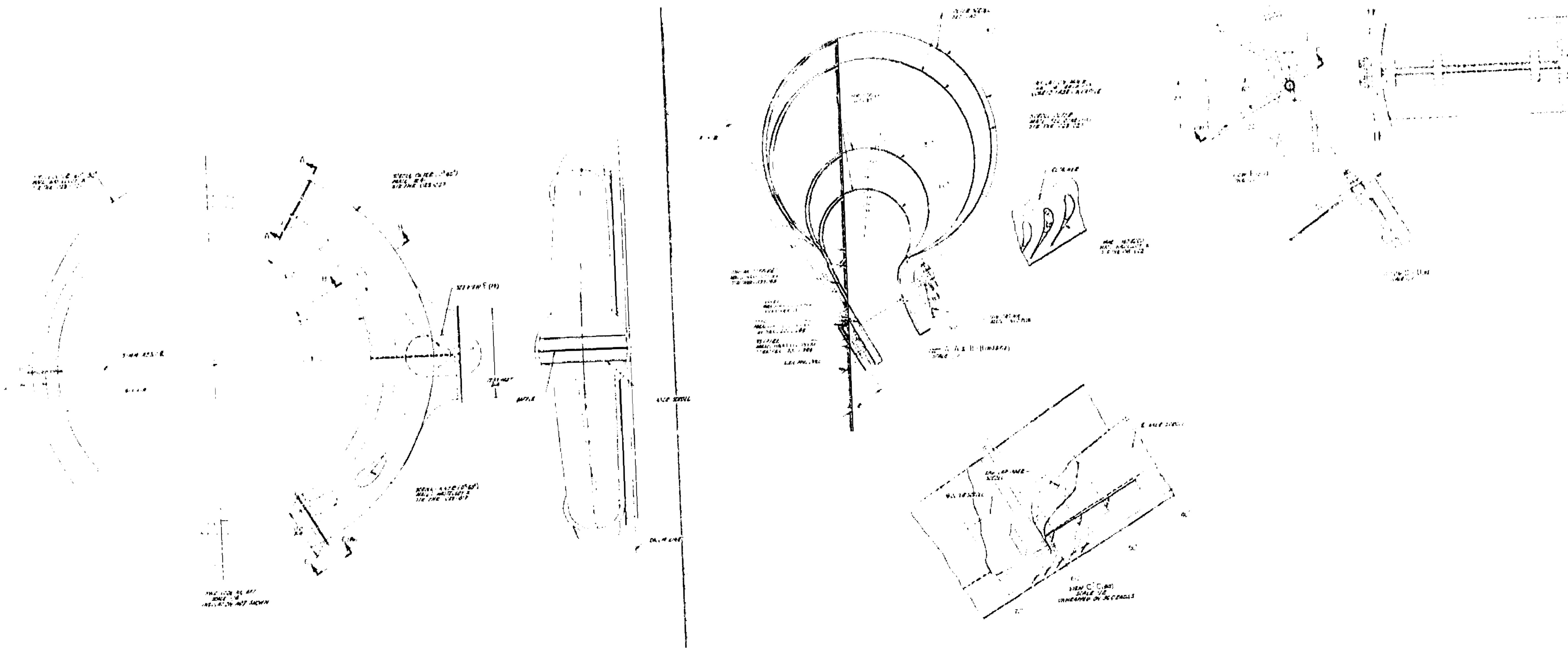

Figure 1. Scroll Configuration.

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FOLDOUT FRAME 1

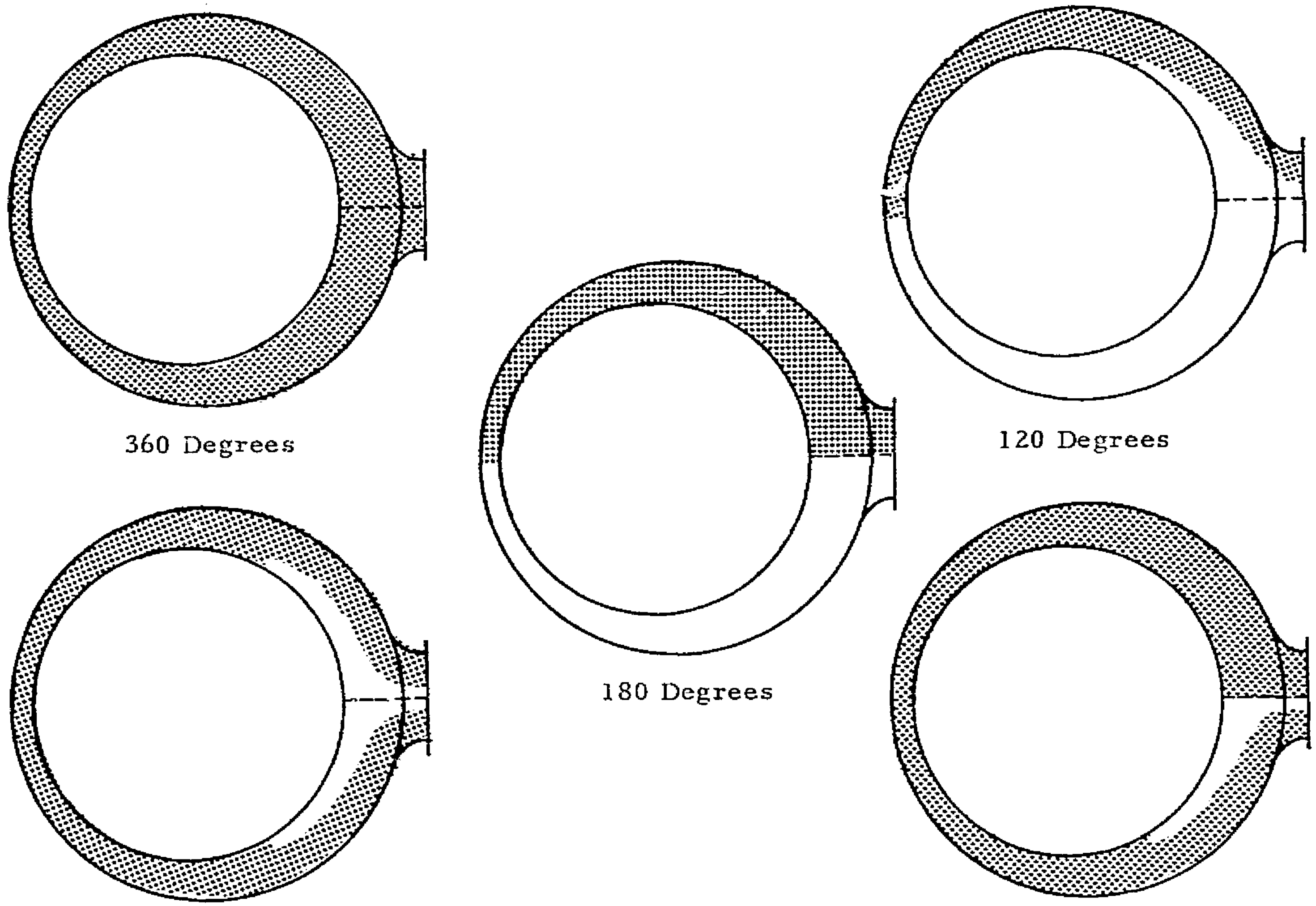

Figure 2 - Scroll Operating Arc Options

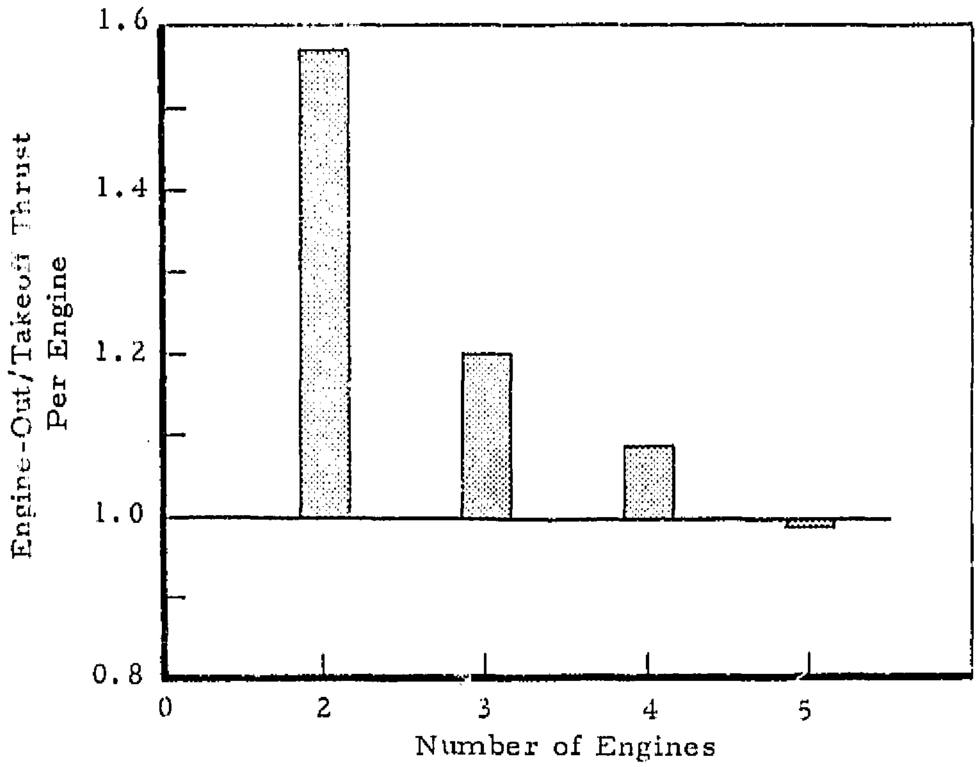

Figure 3 - Contingency Thrusts, Non-Interconnected

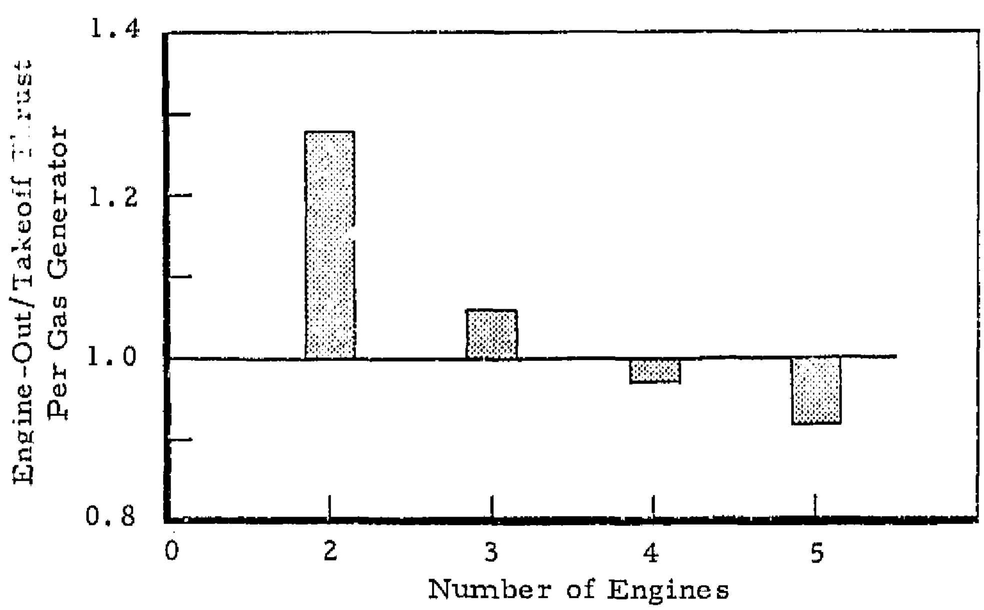

Figure 4 - Contingency Thrusts, Interconnected

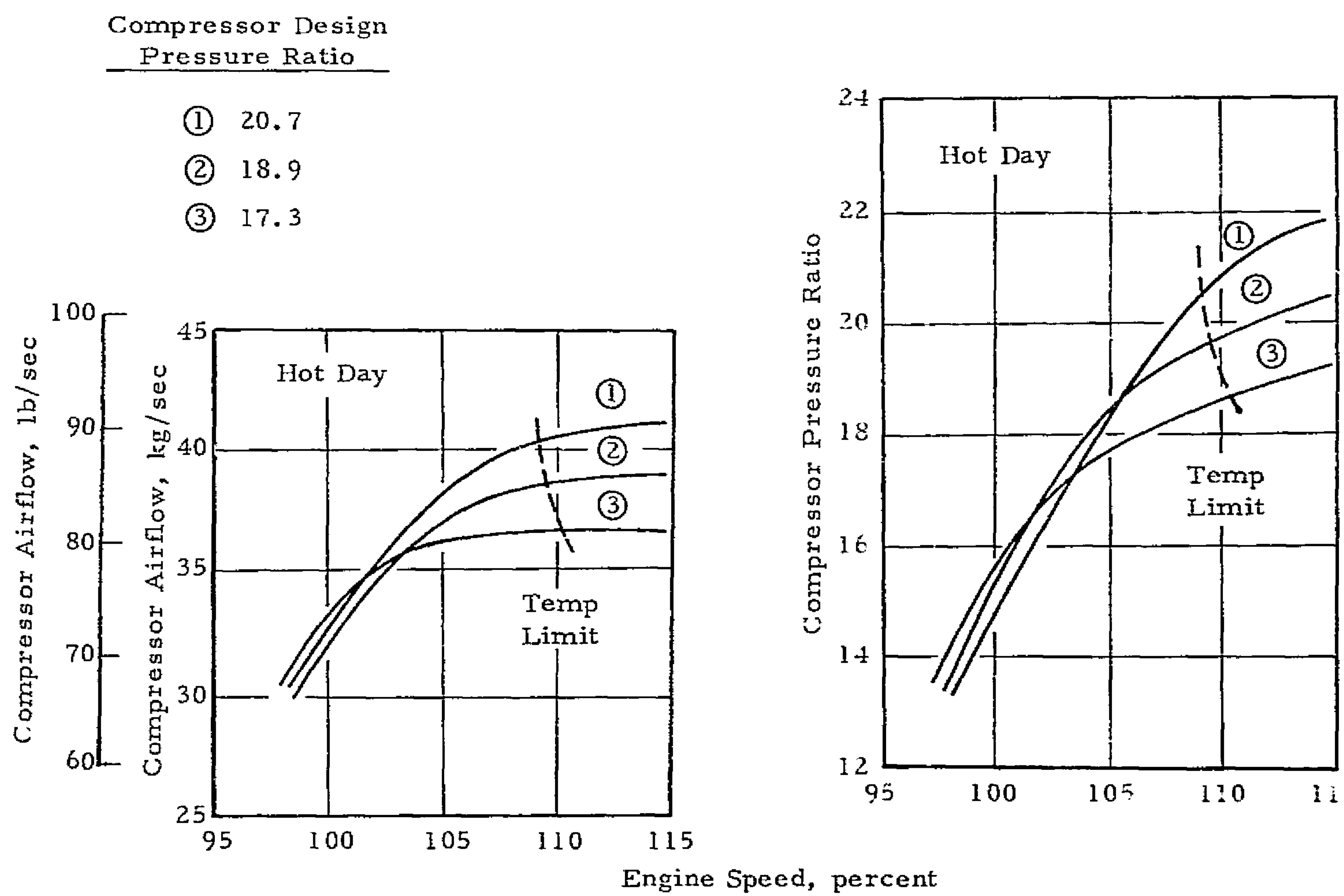

Figure 5 - Operating Characteristics, Rematched Compressors

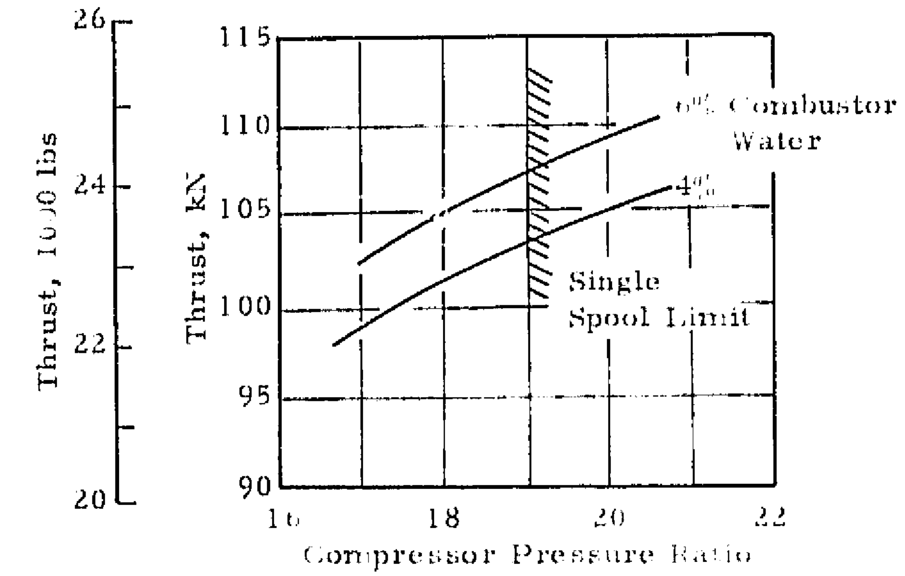

Figure 6 - Engine-Out Thrusts, Rematched Compressor

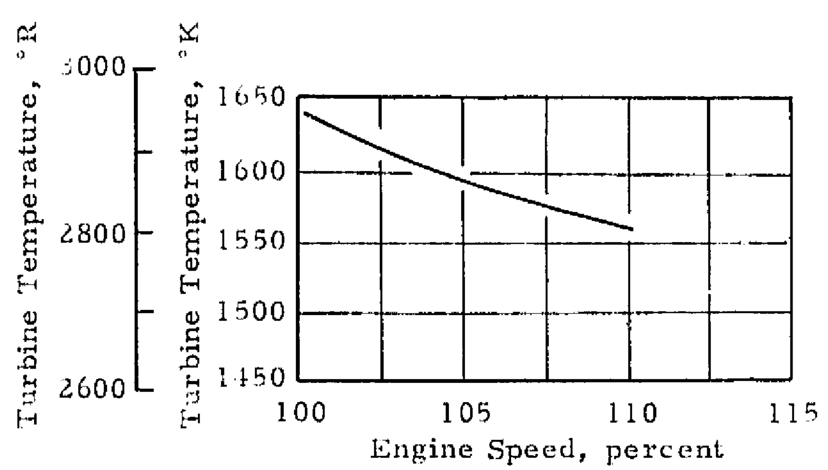

Figure 7 - Engine Turbine Inlet Temperature Limits

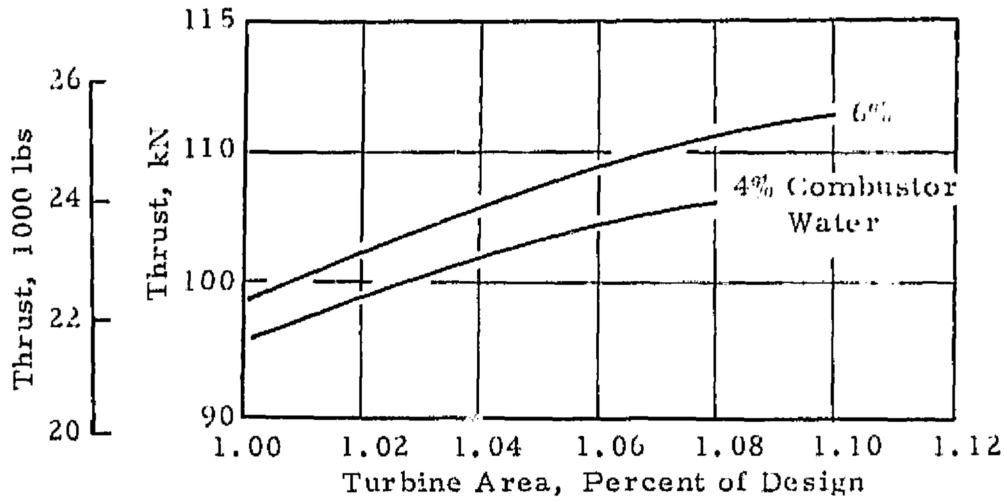

Figure 8 - Engine-Out Thrusts, Turbine Matching

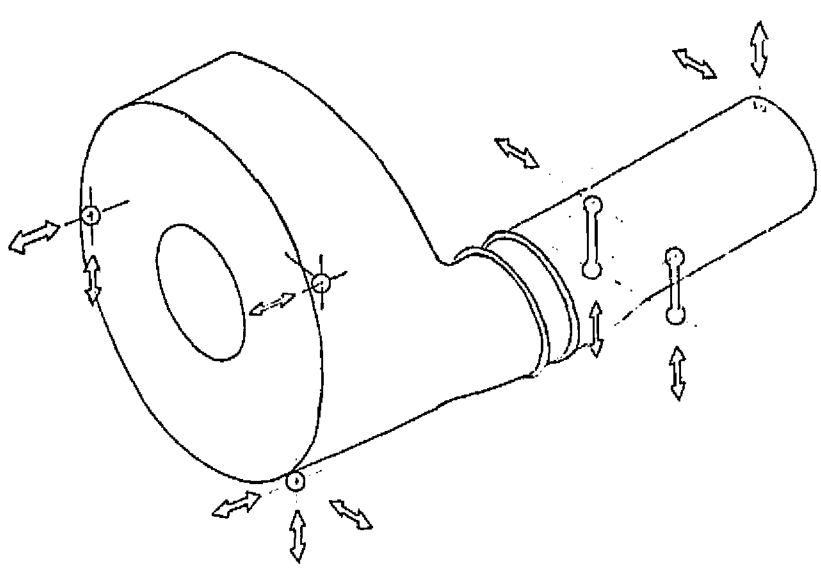

Figure 9 - Close Coupled Mounting System

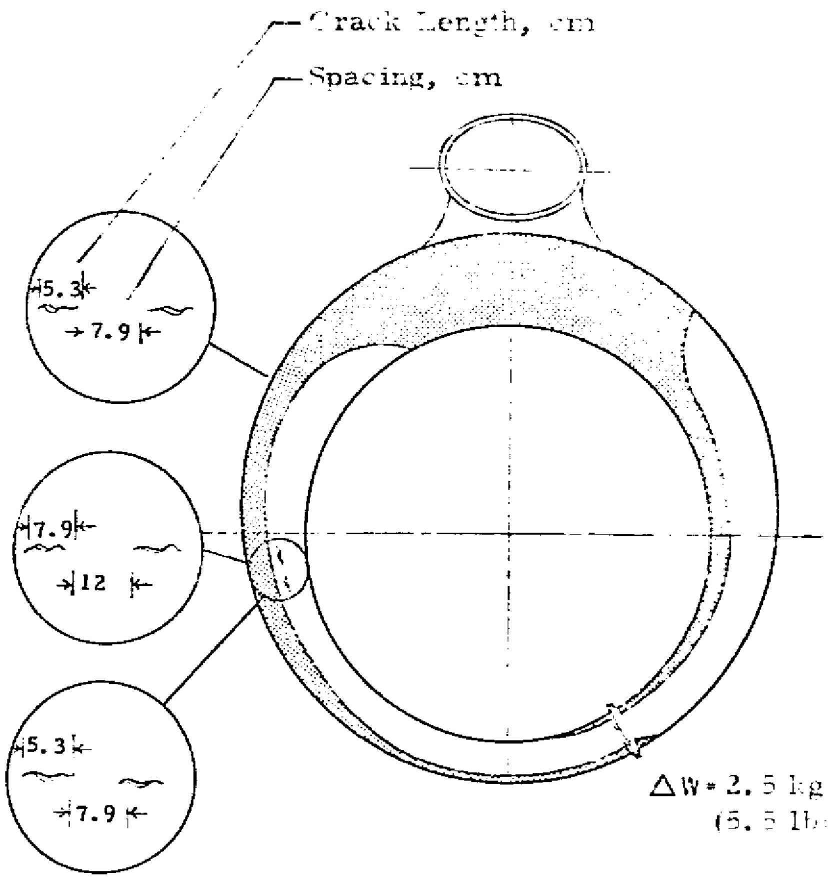

Figure 10 - Crack Tolerance
Original Scroll Design

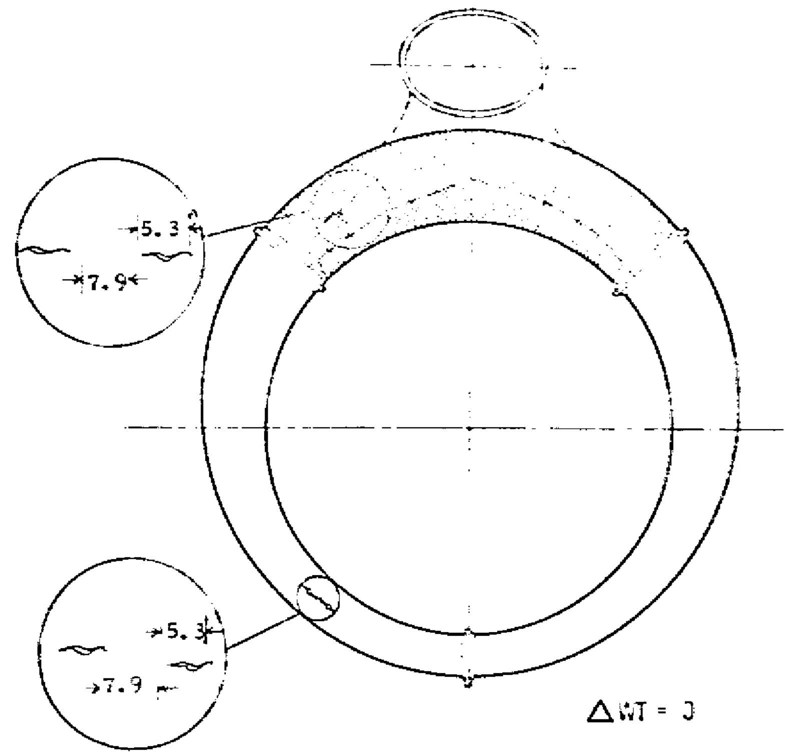

Figure 11 - Crack Tolerance
Redesigned Scroll